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**Rico et al.**

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(54) **APPARATUS TO SUPPORT  
SUPERCONDUCTING WINDINGS IN A  
ROTOR OF AN ELECTROMOTIVE MACHINE**

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2012.

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**H02K 55/04** (2006.01)

**H02K 5/22** (2006.01)

**H02K 55/00** (2006.01)

**H02K 5/20** (2006.01)

(52) **U.S. Cl.**

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(2013.01); **H02K 55/00** (2013.01); **Y02E 40/625**  
(2013.01)

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H02K 5/20; H02K 5/22; H02K 55/00; H02K  
5/04

USPC ..... 310/89, 91, 194, 214  
See application file for complete search history.

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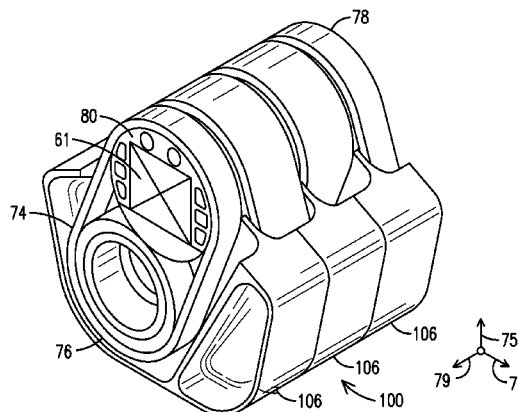
*Primary Examiner* — Dang Le

*Assistant Examiner* — Rashad Johnson

(57) **ABSTRACT**

An apparatus (structure) is provided to support a superconductor winding (61) of an electromotive machine. One or more elongated loops (74) and appropriate support structure (120) may be arranged to provide radial and tangential support to the superconducting winding (61). The elongated loops may be made of a material substantially resistant to heat flow. An axially-extending base assembly (100) may be arranged to anchor loops (74) with respect to the rotor core at a proximate end (76) of the elongated loops. A cradle (80) may be configured to define a recess (82) to receive the superconductor winding and to support the elongated loops at a distal end (78) of the loops.

**26 Claims, 7 Drawing Sheets**



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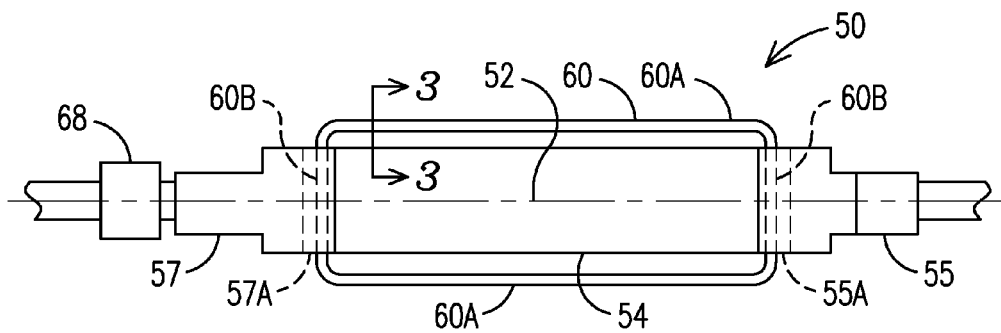


FIG. 1

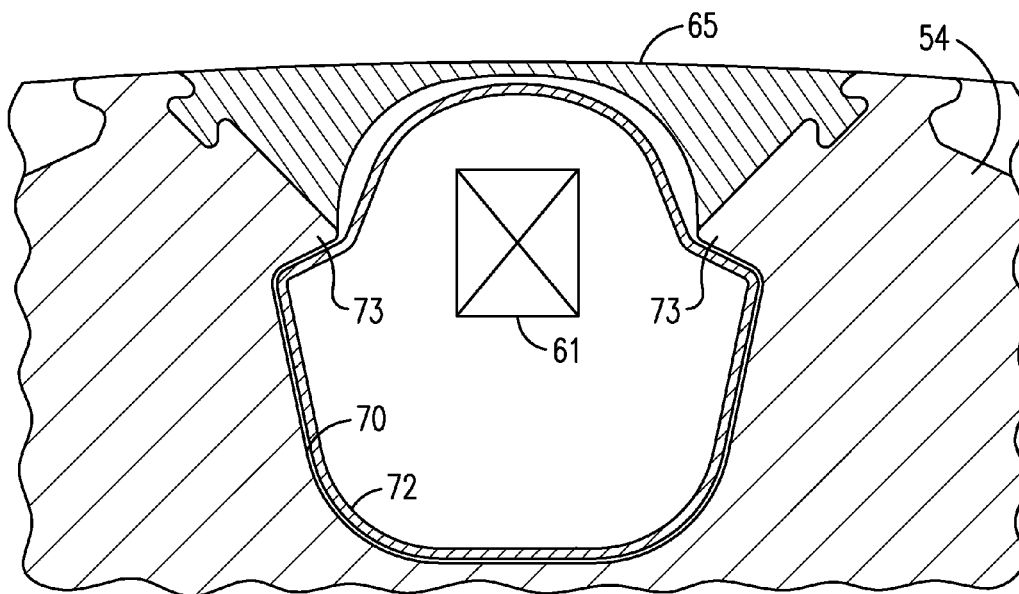


FIG. 2

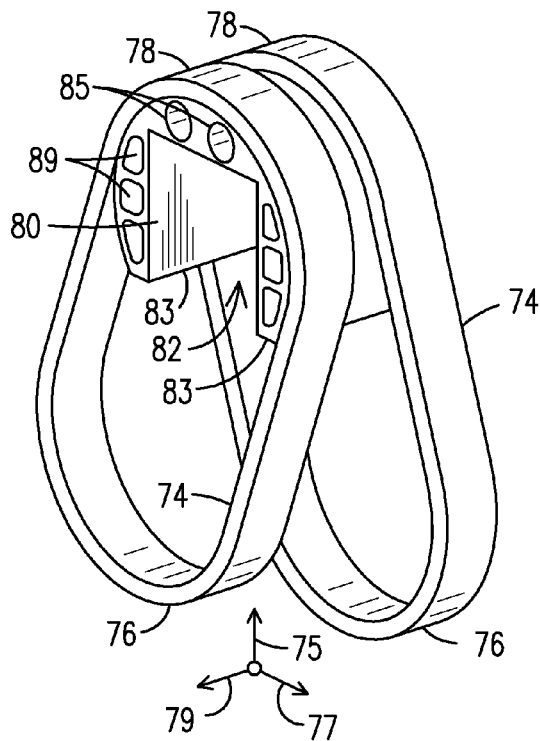


FIG. 3

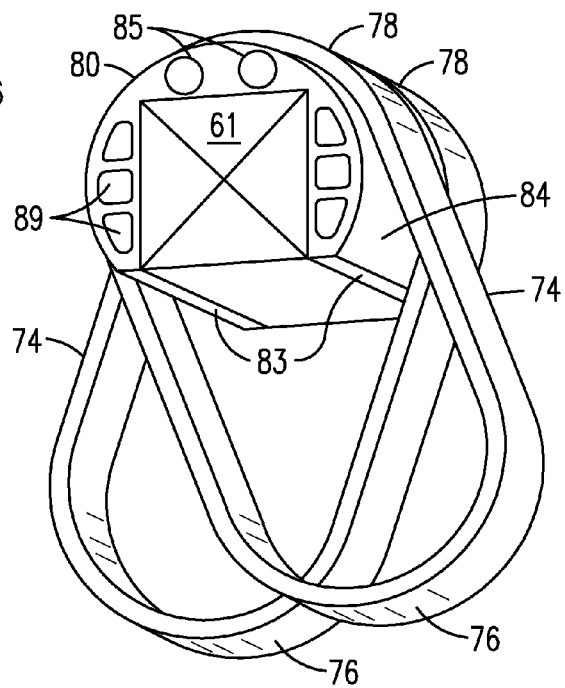


FIG. 4

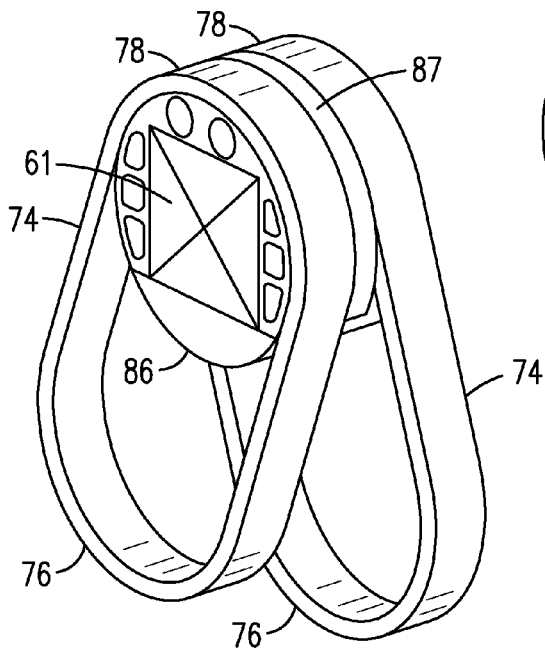


FIG. 5

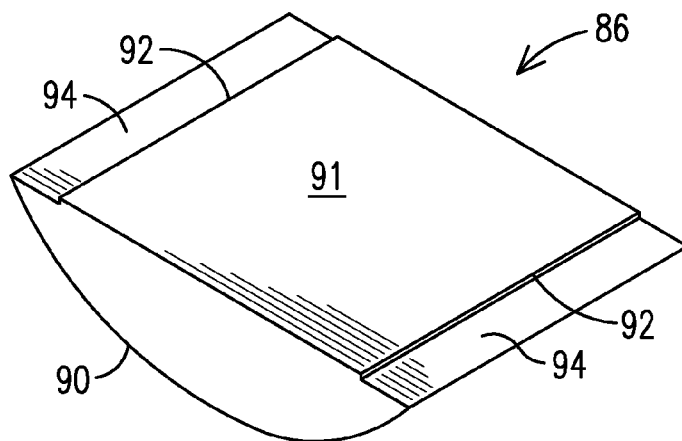


FIG. 6

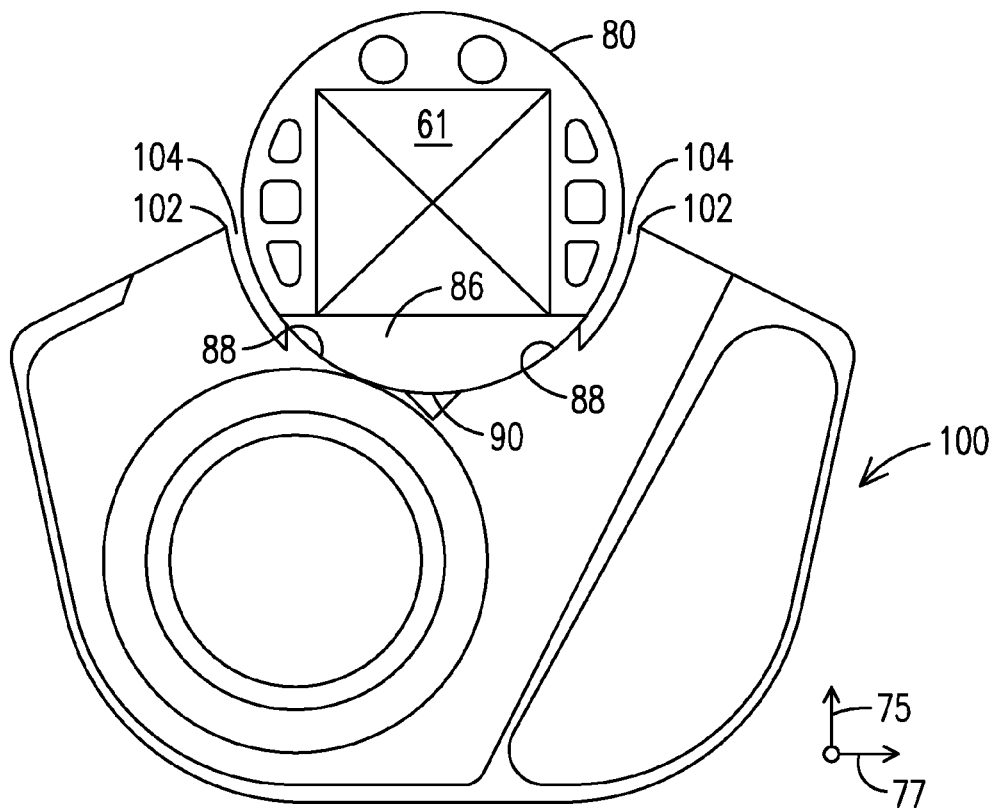


FIG. 7

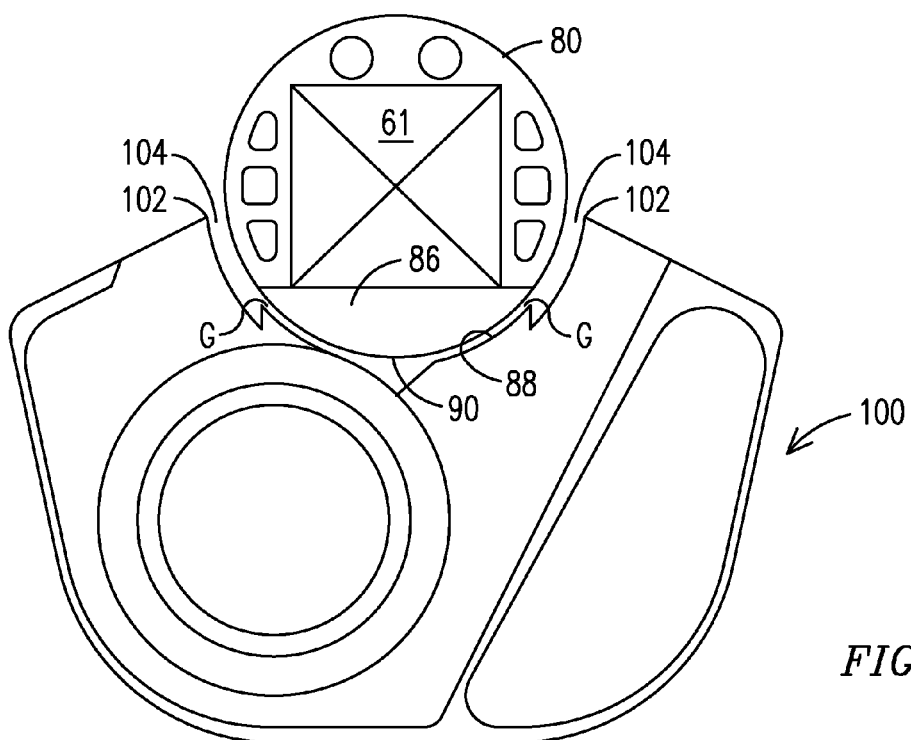


FIG. 8

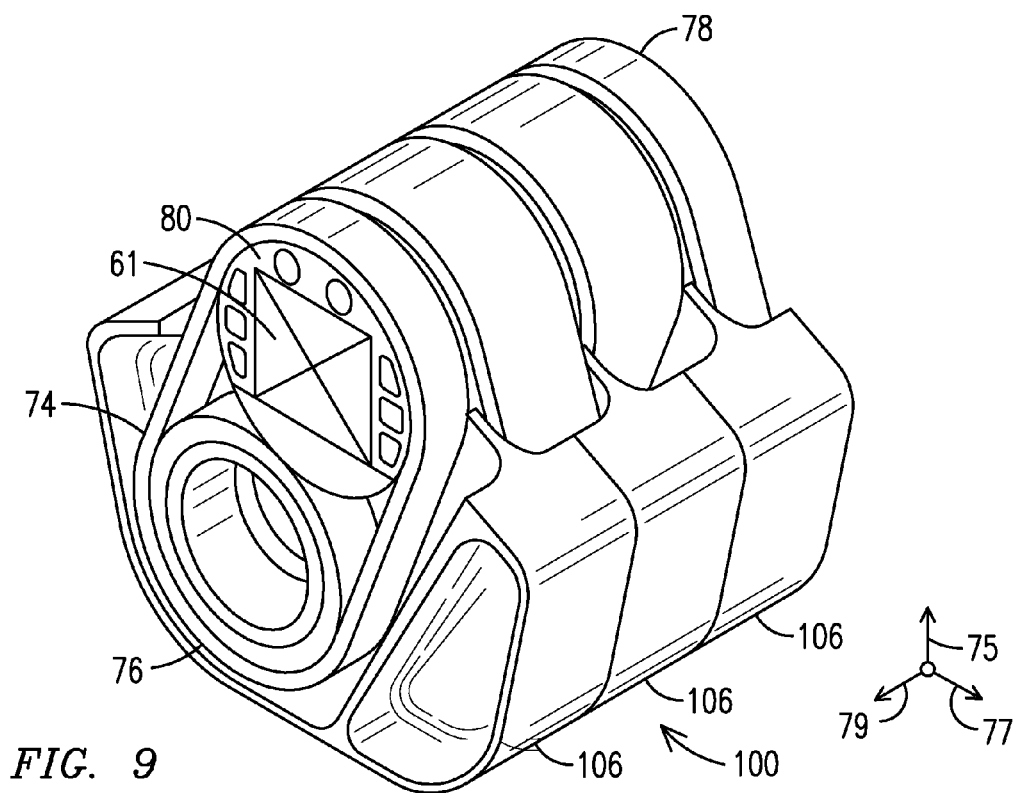


FIG. 9

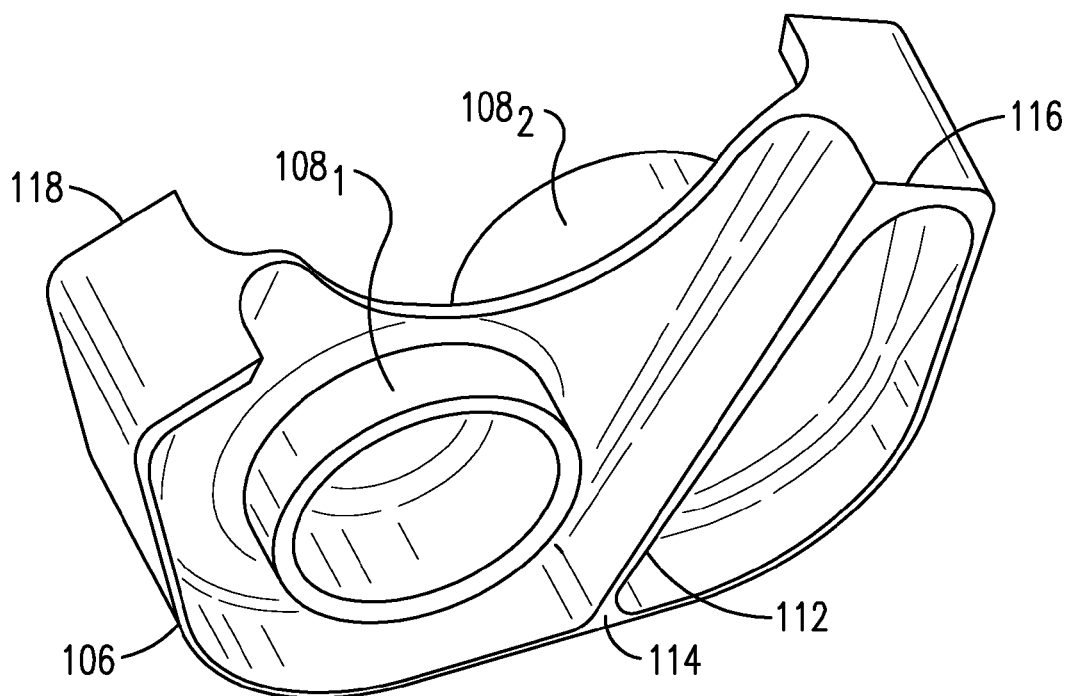


FIG. 10

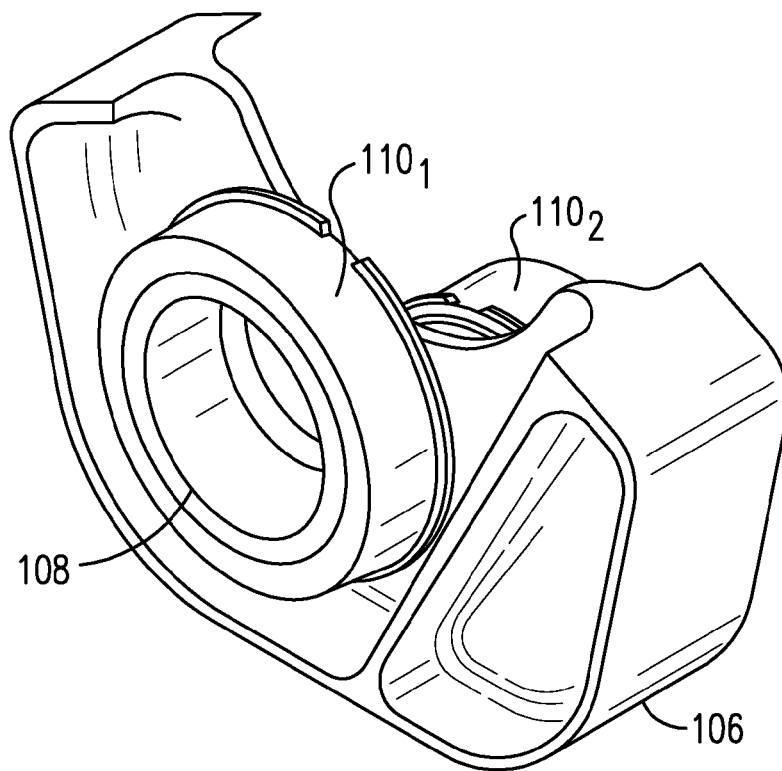


FIG. 11

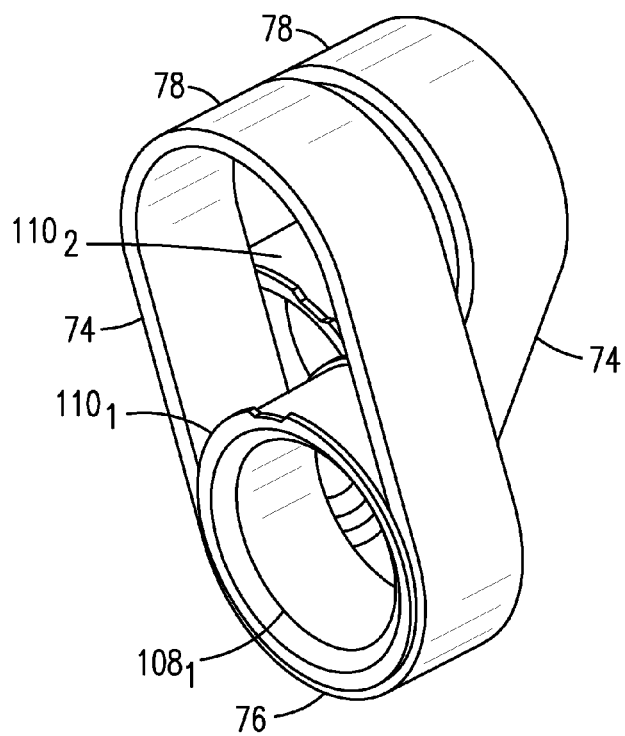


FIG. 12

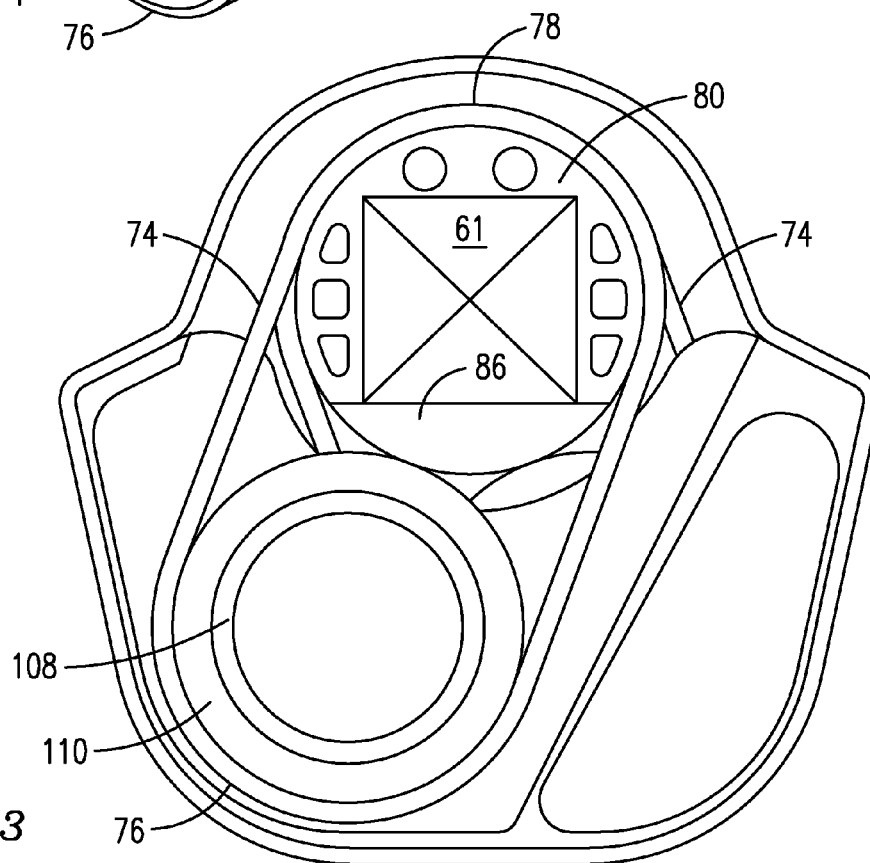


FIG. 13



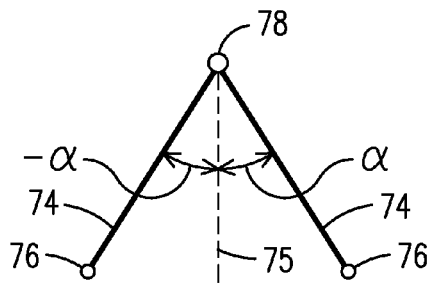


FIG. 14

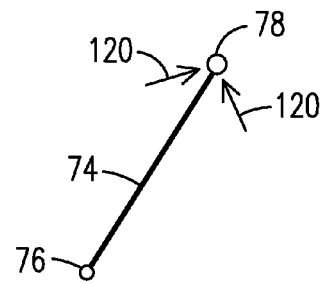


FIG. 16

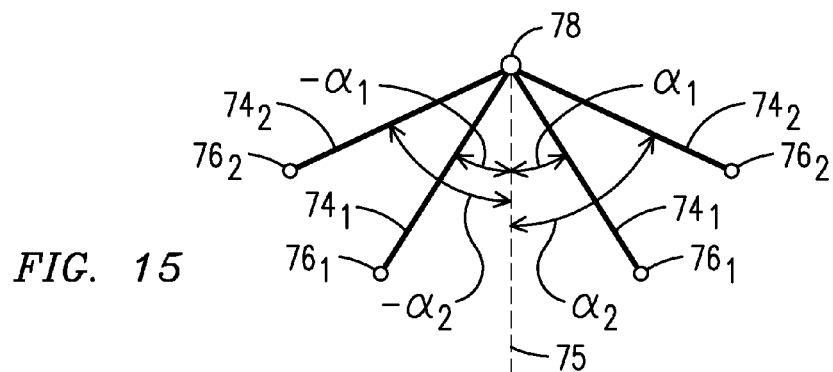


FIG. 15

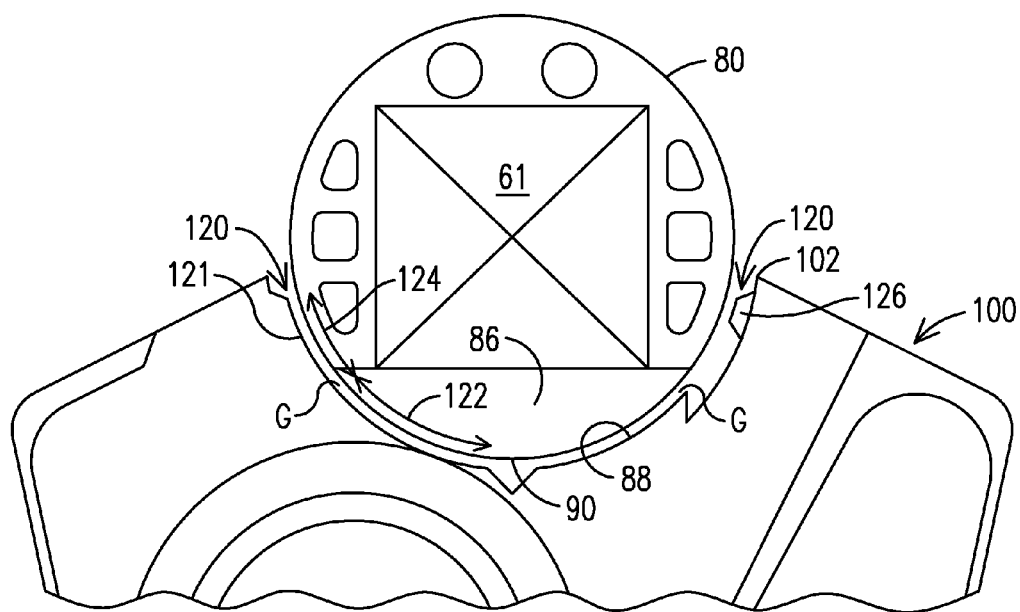


FIG. 17

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## APPARATUS TO SUPPORT SUPERCONDUCTING WINDINGS IN A ROTOR OF AN ELECTROMOTIVE MACHINE

This application claims benefit of the 2 Jul. 2012 filing date  
of U.S. provisional patent application No. 61/666,970.

### FIELD OF INVENTION

The invention relates generally to electromotive machines,  
such as electric generators, motors, and, more particularly, to  
apparatus (e.g., mechanical structures) arranged to support  
and thermally isolate superconducting rotor windings in a  
rotor of the machine.

### BACKGROUND OF THE INVENTION

To increase output and efficiency and reduce machine size  
and weight, superconducting rotor windings with virtually no  
electrical resistance have been developed. These winding are  
commonly referred to as high-temperature superconducting  
(HTS) windings (distinguished from low temperature super-  
conducting materials that achieve a superconducting state at a  
lower temperature). It is preferred to use high-temperature  
superconducting materials since their cooling requirements  
are less severe.

Although the HTS rotor windings (coils) exhibit a rela-  
tively low resistance to electrical current flow, they are sen-  
sitive to mechanical bending and tensile stresses that can  
cause premature degradation and winding failure (e.g., an  
electrically open circuit). For example, it is necessary to form  
bends in the HTS rotor windings that circumscribe the core.  
Stresses are induced at these bends. Normal rotor torque,  
transient fault condition torques and transient magnetic fields  
induce additional stress forces in the rotor windings. Also, the  
HTS rotor winding may be subjected to over-speed forces  
during rotor balancing procedures and occasional over-speed  
conditions during power generation operation. These over-  
speed and fault conditions substantially increase force loads  
on the rotor windings beyond the loads experienced during  
normal operating conditions. These operating conditions  
must be considered in the design of the HTS rotor windings  
and associated support structures.

To maintain the superconducting conductors at or below  
their critical temperature, coolant flow paths carrying coolant  
supplied from a cryogenic cooler are disposed adjacent or  
proximate the windings. Typical coolants may comprise liq-  
uid helium, liquid nitrogen or liquid neon. Maintaining the  
structural integrity of the superconducting rotor windings and  
associated support structure against static and dynamic loads  
presents a substantial challenge to the development of a high  
temperature superconducting electromotive machine.

In view of the foregoing considerations, it is desirable the  
HTS rotor windings be adequately supported by a winding  
support system designed to withstand the forces, stresses,  
strains and cyclical loads of normal and fault condition op-  
eration described above. Moreover, the support system should  
ensure that the windings do not prematurely crack, fatigue or  
break. It is further desirable that the winding support structure  
appropriately thermally isolates the “warm” rotor (typically  
operating above room temperature) from the cryogenically-  
cooled HTS superconducting windings to maintain the wind-  
ings at or below their critical temperature.

### BRIEF DESCRIPTION OF THE DRAWINGS

The invention is explained in the following description in  
view of the drawings that show:

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FIG. 1 is a schematic representation of an example rotor, as  
may be used in a superconducting electromotive machine  
embodying aspects of the present invention.

FIG. 2 is a cross-sectional view along a plane 3-3 of FIG. 1.

FIG. 3 is an isometric view illustrating an example pair of  
elongated loops, which may be connected at their respective  
distal ends to a cradle, and which loops may be arranged to  
provide both radial and tangential support to the cradle.

FIG. 4 is an isometric view further illustrating a supercon-  
ducting winding, which may be disposed in a recess in the  
cradle.

FIG. 5 is an isometric view further illustrating an example  
pedestal support, which may be arranged to close the bottom  
of the recess in the cradle, and may provide a surface to  
support the superconducting winding disposed in the cradle.

FIG. 6 is an isometric view illustrating example structural  
details in connection with the pedestal support.

FIG. 7 is an elevational view illustrating an example base  
assembly, which may be arranged to support during static  
conditions or relatively low-speed rotor operation the pedes-  
tal, and which in one example embodiment may provide a  
tubular coupling arrangement to anchor the respective proxi-  
mate ends of the elongated loops.

FIG. 8 corresponds to the elevational view of FIG. 7 and  
further illustrates a gap, which may be formed during normal  
rotor operation between the base assembly and the pedestal,  
and which effectively reduces thermal transfer from the rotor  
to the superconducting winding.

FIG. 9 is an isometric view illustrating a plurality of  
example base modules, which may be axially interconnected  
to one another to form the base assembly.

FIG. 10 is an isometric view illustrating example structural  
details in connection with a base module.

FIG. 11 is an isometric view further illustrating an example  
pair of female couplers in connection with a tubular coupling,  
which may be provided by the base module.

FIG. 12 is an isometric view illustrating a visually-simpli-  
fied connection arrangement between the respective proxi-  
mate ends of the elongated loops and the pair of female  
couplers.

FIG. 13 is an elevational view illustrating an example  
assembly of at least some of the various components illus-  
trated in some of the preceding FIGs, which in combination  
form a winding support apparatus embodying aspects of the  
present invention, such as may be effective to substantially  
reduce heat transfer from the “warm” rotor core to the super-  
conducting winding while mechanically withstanding forces,  
stresses, strains and cyclical loads that may develop during  
normal and/or fault conditions of the machine.

FIG. 14 is simplified free-body diagram for conceptualiz-  
ing load-carrying aspects provided by the example pair of  
elongated loops, which in accordance with aspects of the  
present invention may allow transferring radial and tangential  
loads while substantially reducing heat transfer from the  
“warm” rotor core to the superconducting winding.

FIG. 15 is simplified free-body diagram for conceptualiz-  
ing load-carrying aspects regarding another example embodi-  
ment of the present invention where groupings of elongated  
loops (e.g., two or more loops), may allow transferring the  
radial and tangential loads.

FIG. 16 is simplified free-body diagram for conceptualiz-  
ing load-carrying aspects regarding still another example  
embodiment of the present invention, where a single elon-  
gated loop in combination with appropriate support structure  
may allow transferring the radial and tangential loads.

FIG. 17 is an elevational view illustrating an example base  
assembly, adapted to include appropriate support structure

which may be used in conjunction with a single elongated loop to carry the centrifugal and tangential loads.

#### DETAILED DESCRIPTION OF THE INVENTION

A superconducting rotor **50** embodying aspects of the invention is shown in FIG. 1. The superconducting rotor **50** defines a longitudinally-extending axis **52** (e.g., axial direction) and comprises a generally cylindrically-shaped core **54** and coaxially aligned rotor end sections **55** and **57** each attached to an end surface of the core **54**. A material of the core **54** exhibits a high magnetic permeability, e.g. a ferromagnetic material such as iron.

In one example embodiment, the superconducting rotor **50** may further comprise a generally longitudinally-extending, racetrack-shaped superconducting coil or winding **60** comprising generally linear axially-extending winding segments **60A** connected by radially-extending winding segments **60B** (e.g., radial direction), as may extend through respective spacers **55A** and **57A** disposed at the respective end sections **55** and **57** of rotor **50**. It will be appreciated that aspects of the present invention are not limited to racetrack-shaped winding configurations. It will be appreciated that other winding configurations may be employed, such as saddle-shaped configurations, and other configurations which may accommodate multiple windings.

In one example embodiment, superconducting rotor **50** may be arranged as a rotor of an electric generator and superconducting winding **60** may be arranged as an electric generator field (rotor) winding. One of the end sections **55** or **57** may include a turbine coupling for connecting rotor **50** to a prime mover for supplying rotational energy to the superconducting rotor **50** for generating electricity in a stator. In another embodiment, superconducting rotor **50** may be arranged as a rotor of a motor for producing rotational energy responsive to an electric field generated in a surrounding stator winding.

In one example embodiment, end section **57** may include a cryogenic transfer coupling **68**. When superconducting rotor **50** is rotating during operation of the dynamoelectric machine, cryogenic transfer coupling **68**, which may comprise a stationary portion and a rotating portion (the individual portions not illustrated in FIG. 1), supplies cooling fluid (e.g., cryogenic fluid) from a cryogenic cooler (not shown) to closed coolant flow paths or channels in the superconducting winding **60** to maintain the superconducting winding **60** at or below its critical temperature. The coolant flows through the coolant channels, circulates back to the cryogenic cooler where the coolant temperature is reduced and returns to the coolant channels.

The required cooling capacity of the cryogenic cooler is directly related to the heat transferred from the “warm” rotor core **54** and its surroundings to the superconducting winding **60** during operation of the superconducting generator. The inventors of the present invention propose a winding support structure arranged to substantially reduce such heat transfer during normal and transient operational conditions so that, for example, one can reduce the required cooler capacity and the energy consumed by the cooler to cool the cryogenic fluid.

FIG. 2 is a cross-sectional view along a plane 3-3 of FIG. 1. Because of the various components involved, the figures to be described below will be used for gradually introducing components of an example embodiment of a winding support apparatus embodying aspects of the present invention. The idea is to gradually introduce components that form the winding support apparatus to avoid overwhelming the reader.

FIG. 2 illustrates a cavity **70**, as may be constructed in rotor core **54**. Cavity **70** may be configured to receive a cryostat **72**, as may be used to provide a vacuum to limit radiative heat transfer from rotor core **54** to a superconducting block **61**, which in this example embodiment makes up superconducting winding **60**. In one example embodiment cryostat **72** may be made from a non-magnetic metal or metal alloy, such as non-magnetic steel.

Cavity **70** may be configured to define appropriately shaped restraining structures, such as shoulders **73**, (e.g., protuberances) configured to engage a corresponding surface of cryostat **72** to retain cryostat **72** in cavity **70** under centrifugal forces that develop during rotor operation. Although one superconducting block is illustrated in the FIGs, it will be appreciated that aspects of the present invention are not limited to any specific number of superconducting blocks since other example embodiments may have more than one superconducting block.

Superconducting block **61** (winding) may be made up of a plurality of superconducting tapes formed from a known superconducting HTS material. As would be understood by those skilled in the art, suitable adhesives and techniques may be used to assemble and retain the tapes in a desired configuration. The description below proceeds to introduce example components for mechanically supporting superconducting winding **61** while substantially reducing heat transfer to superconducting winding **61** from the “warm” rotor core **54**. FIG. 2 further illustrates an electromagnetic shield **65**, which may be connected to rotor **54** to shield superconducting winding **61** from transient electromagnetic fields. Shield **65** may be made from an electrically conductive and non-magnetic material, such as aluminum or copper.

FIG. 3 illustrates a pair of elongated loops **74**, as may be formed from a material having a relatively high tensile strength at low-temperatures and having high thermal resistivity (e.g., a low thermal conductivity compared to the thermal conductivity of stainless steel), such as a fiber-reinforced polymer (FRP) material. Accordingly, FRP material is one example of a fiber-reinforced composite material substantially resistant to heat flow.

Each loop **74** may extend at a respective angle (e.g., respective congruent angles, see description related to the free-body diagram discussed in the context of FIG. 14) relative to a radial axis **75** from a proximate end **76** to a distal end **78** to symmetrically provide both radial and tangential support to superconducting winding **61** (not shown in FIG. 3). In this example, distal ends **78** constitute respective radially distal ends relative to rotor axis **52** (FIG. 1). The composite material of loops **74** substantially resists heat flow from the warm rotor core **54** to superconducting winding **61**.

As should be appreciated from the description that follows, each loop **74** may be arranged to effectively transfer to the rotor core **54** centrifugal (e.g., as may develop along radial axis **75**) and tangential loads (e.g., as may develop along a tangential direction **77**, which is orthogonal relative to radial direction **75** and axial direction **79**) exerted on superconducting winding **61**.

Although the description below, for the sake of simplicity of illustration and explanation, focuses on example pairs of elongated loops, it will be appreciated that aspects of the present invention are not limited to pairs of elongated loops **74**. For example, it is contemplated than in lieu of just a singular elongated loop angled at an angle  $\alpha$  with respect to radial axis **75** (FIG. 14) and another singular elongated loop angled at an angle  $-\alpha$  with respect to radial axis **75**, one may utilize a first group of elongated loops **74**<sub>1</sub>, **74**<sub>2</sub> (e.g., two or more loops) at respective positive angles  $\alpha_1$ ,  $\alpha_2$  with respect

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to radial axis **75**, and a second group of elongated loops **74<sub>1</sub>**, **74<sub>2</sub>** at respective negative angles with respect to radial axis **75**  $-\alpha_1$ ,  $-\alpha_2$ .

Additionally, although example congruent angles (e.g.,  $\alpha$ ,  $-\alpha$ ) are illustrated in the figures, it will be further appreciated that aspects of the present invention are not limited to a symmetrical angular arrangement for the elongated loops. For example, there may be applications where the arrangement of the elongated loops may be asymmetrically chosen either in terms of asymmetrical angles relative to the radial axis and/or in terms of asymmetrical distribution (e.g., a group of two loops on one side of the radial axis and just one loop on the other side of the radial axis) to, for example, enhance the lateral support on the one side relative to the other side (e.g., asymmetrical support). Accordingly, it will be appreciated that aspects of the present invention are not limited to having an equal number of loops per side and/or having a symmetrical angular arrangement for the elongated loops. Moreover, depending on the needs of a given application, one may additionally employ elongated loops along the radial axis in combination with the loops angled with respect to the radial axis **75**.

FIG. **3** further shows an example embodiment of a cradle **80**, which includes a recess **82** to receive superconducting winding **61**, as shown in FIG. **4**. In one example embodiment, cradle **80** may include an arch-shaped exterior surface **84** (better appreciated in FIG. **4**), which can receive the respective distal ends **78** of loops **74**. Cradle **80** may further include a pair of respective bottom surfaces **83** and may include one or more passageways **85** for passing a suitable cryogen fluid. It will be appreciated by one skilled in the art that aspects of the present invention are not limited to any specific arrangement in connection with passageways **85**. For example, it is contemplated that cooling passageways could be constructed within winding **61**. In one example embodiment, cradle **80** may include one or more weight-reducing openings **89**. Cradle **80** may be made from aluminum, aluminum alloy, or other suitable relatively light-weight, fiber-reinforced composite material. The description below proceeds to introduce further components for mechanically supporting superconducting winding **61** while substantially reducing heat transfer to superconducting winding **61** from the “warm” rotor core **54**.

FIG. **5** shows a pedestal support **86** having a first planar surface **91** (FIG. **6**), which closes the bottom of recess **82** (FIG. **3**) in cradle **80** and provides a pedestal to support superconducting winding **61**. Pedestal **86** may be made from a thermoplastic polymer material or similar thermally-isolating material. Pedestal support **86** further includes a respective pair of steps **92**, arranged to define a pair of laterally-disposed planar surfaces **94**, which may receive corresponding bottom surfaces **83** (FIG. **4**) of cradle **80**. Pedestal support **86** may further include an arch-shaped surface **90** (FIG. **6**), which in one example embodiment is supported by a base assembly **100** (FIG. **7**). It will be appreciated that aspects of the present invention are not limited to any specific geometric configuration in connection with pedestal support **86** since other geometric configurations may work equally effective for pedestal support **86**.

For example, during static conditions (no rotor rotation) or during rotational conditions comprising relatively low revolution per minute (RPM) rotation of the rotor (e.g., in a range from approximately 100 RPM to approximately 300 RPM), pedestal support **86** may be in contact with one or more seats **88**, (FIG. **7**) which may be constructed along at least one or more portions on a corresponding periphery **102** of base assembly **100**. Conversely, during rotational conditions com-

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prising relatively higher revolution per minute (RPM) rotation of the rotor (e.g., approximately exceeding the foregoing example range), in response to centrifugal forces, as illustrated in FIG. **8**, a relatively small gap (G) (e.g., in the order of a few millimeters) may be formed between surface **90** of pedestal support **86** and seats **88**, and this gap may be effective to reduce conductive thermal transfer from the “warm” rotor core **54** to superconducting winding **61**.

It will be appreciated that in one example embodiment respective end-segments **104** of periphery **102** effectively constitute respective mechanical stops to restrain excess lateral motion of cradle **80**, which could occur during transient bumping conditions of the machine.

Although the description thus far has referred to pairs or groups of elongated loops **74** disposed to carry centrifugal and tangential loads, it is contemplated that aspects of the present invention could be implemented by way of a single loop **74** and appropriate support structure (other than (and/or in combination with) additional elongated loops), as may be conceptually represented by arrows **120** (FIG. **16**), arranged to jointly carry such centrifugal and tangential loads.

In one example embodiment, as illustrated in FIG. **17**, support structure **120** may comprise one or more bumpers, which may be part of or otherwise constructed on base assembly **100** to provide tangential and/or radial support. Support structure **120** may be implemented in various ways. For example, support structure **120** may be implemented as a continuous bumper **121**. This continuous structure would provide a dual functionality. For example, a first bumper portion **122** would provide the support function provided by seat **88** during the static conditions or relatively low-speed rotor operation, and a second bumper portion **124** would provide tangential load and/or radial support, which otherwise would have been carried by a further elongated loop or further group of such loops. In this example embodiment, second bumper portion **124** may be viewed as an extension of seat **88**, and bumpers portions **122** and **124** would define at least a portion of periphery **102** of base assembly **100**.

In one alternative embodiment, support structure **120** may be implemented as a discrete bumper structure along periphery **102**. For example, one or more discrete bumpers **126** would provide the tangential support and/or radial support, which otherwise would have been carried by a further elongated loop or further group of such loops. It will be appreciated that such further elongated loop or groups of elongated loops described above may be broadly conceptualized as example embodiments of support structure **120**.

Base assembly **100** may be made from any of various materials, which may comprise a relatively wide range of thermal conductivity characteristics, such as steel, aluminum, aluminum alloy, fiber-reinforced composite material. In example cases where base assembly **100** is made from a material having a relatively high thermal conductivity, support structure **120**, for example, may optionally include a coating of an appropriate thermally isolating material, or support structure **120** may be optionally made of a material having lower thermal conductivity relative to the thermal conductivity of base assembly **100**. In other example cases, where base assembly **100** is made from a material already comprising a relatively low thermal conductivity (e.g., fiber-reinforced composite), further thermal isolation need not be used in connection with support structure **120**.

FIG. **5** further illustrates a spacer **87**, which may be mounted on cradle **80** and may be interposed to maintain axial separation between the respective elongated loops **74** to avoid a possibility of mechanical interference between axially-neighboring loops **74**. Spacer **87** may be made from alumi-

num, an aluminum alloy, or other suitable relatively lightweight, fiber-reinforced composite material.

The description thus far provided has focused on example structures for supporting the respective distal ends 78 of elongated loops 74 and associated structures such as cradle 80, etc. The description below will proceed to discuss example structures for supporting the respective proximate ends 76 of elongated loops 74 and associated structures.

FIG. 9 shows an isometric view of base assembly 100, which in one example embodiment is made up of a plurality of base modules 106 configured to anchor with respect to the rotor core each loop 74 at its respective proximate end 76. In one example embodiment, the plurality of base modules 106 may form an axially-extending anchoring beam, and such modules may be conceptually analogized to Lego-like interlocking building blocks. It will be appreciated that the modular aspects of base assembly 100 are conducive to facilitate the routing of the axially-extending winding segments 60 (FIG. 1) of superconducting winding 61.

Base assembly 100 may be made from any of various materials, such as steel, aluminum, aluminum alloy, fiber-reinforced composite material and may be configured to be enclosed by cryostat 72, where base assembly 100 is retained by shoulders 73 (FIG. 2) together with cryostat 72 in cavity 70 under centrifugal forces that develop during rotor operation. In one example embodiment, cryostat 72 may in part be configured to enclose base assembly 100 and may be further configured to extend outside cavity 70 to form a vacuum about the winding support apparatus and the superconductor winding.

FIG. 10 is an isometric view of an example base module 106, which in combination with additional base modules may form base assembly 100 (FIG. 9). In one example embodiment, each base module 106 may include a tubular coupling arrangement configured to receive the respective proximate ends 76 of loop pair 74 and to provide a mechanical connection (e.g., axial connection) to an adjacent base module.

In one example embodiment, each base module 106 may include a pair of male couplers 108<sub>1</sub>, 108<sub>2</sub> configured to receive at least a portion of respective female couplers 110<sub>1</sub>, 110<sub>2</sub> (FIG. 11), each of which over a portion of its outer diameter receives the proximate end of a corresponding loop 74, as illustrated in FIG. 12. In one example embodiment, one of the male couplers (e.g., male coupler 108<sub>1</sub>) may be disposed on an axially-forward first side (e.g., left side) of base module 106 and the other one of the male couplers (e.g., male coupler 108<sub>2</sub>) may be disposed on axially-rearward second side (right-side) of base module 106, as may be appreciated in FIG. 10. As can be appreciated in FIG. 10, the interior of male couplers 108 may define respective hollow annuli for weight reduction purposes. It will be appreciated that male couplers 108 need not be hollow structures and in certain example embodiments may be non-hollow structures. This arrangement may be alternately repeated by way of additional base modules 106 along the axial direction so that the plurality of base modules 106 forms the axially-extending anchoring beam 100, as shown in FIG. 9.

In one example embodiment, the axial dimension of female couplers 110 may be sufficiently long relative to the axial dimension of male couplers 108 so that the female coupler can also be received by a male coupler of an axially adjacent base module.

In one example embodiment, as may in part be appreciated in FIG. 10, each face of base module 106 may include a pair of diagonal stiffening ribs 112 arranged to structurally stiffen base module 106 relative to bending moments, which may develop by way of the non-centered anchoring arrangement.

For example, the stiffening rib shown in the forward face of base module 106 may extend from a bottom center 114 section towards a shoulder 116 located diagonally opposite with respect to male coupler 108<sub>1</sub>, which is located on the left side of the forward face of base module 106. Although not shown in FIG. 10, the rearward face of base assembly would include a similar rib, which in this case would extend from bottom center 114 towards a shoulder 116 located diagonally opposite with respect to male coupler 108<sub>2</sub>, which is located on the right side of the rear face of base module 106. It will be appreciated that aspects of the present invention are not limited to diagonal stiffening ribs or to any number of ribs being that other structural arrangements may be utilized to effectively increase mechanical strength while reducing the weight of the base assembly.

It will be understood that aspects of the present invention are not limited to a segmented tubular coupling arrangement. For example, one could use a continuous tubular coupling arrangement. For example, one or more continuous rods may be used for anchoring each loop 74 at its respective proximate end 76 in lieu of the foregoing segmented coupling arrangement.

It will be further appreciated that aspects of the present invention are not limited to a base assembly structure 100 disposed in a cryostat in a rotor cavity. For example, it is contemplated that, in lieu of base assembly 100 (and associated tubular coupling structures) accommodated in a rotor cavity, one could construct anchoring structures for the distal ends of loops 74, where such anchoring structures are integral with the rotor core of the machine. In this example embodiment, the cryostat may be externally disposed relative to the rotor core, which is a cylindrical structure, and may be attached to and arranged to surround the rotor core 54 to form the vacuum about the winding support apparatus and the superconductor winding.

It will be appreciated that aspects of the present invention are not limited to a sidewardly-alternating sequence of proximate-end connections along the axial direction for the elongated loops in order to transfer tangential and radial loads to the rotor core. For example, one may arrange axially-adjacent (side-by-side) proximate end anchoring connections for the pair of elongated loops so that the respective proximate ends of such loops may be respectively connected to a single face of a given base assembly, in lieu of connecting to both the axially-forward face of base module 106 and to an axially-rearward face of base module 106.

FIG. 13 is an isometric view illustrating an assembly of at least some of the various components described in the preceding description, which in combination form a winding support apparatus embodying aspects of the present invention, such as may be effective to substantially reduce heat transfer from the "warm" rotor core to the superconducting winding while mechanically withstanding forces, stresses, strains and cyclical loads that may develop during normal and fault conditions of the machine.

FIG. 14 is simplified free-body diagram for conceptualizing load-carrying aspects of the elongated loops 74, which allow transferring radial and tangential loads while substantially reducing heat transfer from the "warm" rotor core to the superconducting winding. For example, each loop 74 may be located at an angle  $\alpha$  relative to radial axis 75. That is, each loop 74 forms a congruous angle on each side of radial axis 75, which allows loop pair 74 to symmetrically carry vectorial components of the radial and lateral loads, which may develop during operation of the machine. Aspects of the present invention, innovatively and advantageously may simplify the number of components which would be involved, if,

for example, one chose to utilize a first assembly dedicated to just carry radial loads and a second assembly dedicated to just carry tangential loads.

While various embodiments of the present invention have been shown and described herein, it will be apparent that such 5 embodiments are provided by way of example only. Numerous variations, changes and substitutions may be made without departing from the invention herein.

The invention claimed is:

1. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromo- 10 tive machine, comprising:

a cradle configured to define a recess to receive the superconductor winding;

at least a first elongated loop and at least a second elongated 15 loop each arranged at a respective angle relative to a radial axis to provide radial and tangential support to the cradle, wherein the elongated loops comprise a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least first loop and said at least second loop at respective distal ends of 20 the elongated loops, wherein the elongated loops comprise individual structures; and

an axially-extending base assembly arranged to anchor said at least first loop and said at least second loop with 25 respect to the rotor core at respective proximate ends of the elongated loops, which proximate ends are respectively located on first and second mutually opposite sides of the radial axis.

2. The apparatus of claim 1, wherein the cradle comprises 30 an arch-shaped exterior surface configured to receive the respective distal ends of the elongated loops.

3. The apparatus of claim 1, further comprising a pedestal arranged to close a bottom side of the recess and support the superconducting winding in the cradle. 35

4. The apparatus of claim 3, wherein the base assembly comprises at least one or more seats arranged to support the pedestal during a static condition of the rotor or during a rotational condition comprising a relatively low revolution 40 per minute (RPM) of the rotor.

5. The apparatus of claim 4, wherein during a rotational condition above the relatively low revolution per minute of the rotor, a gap is formed between said at least one or more seats of the base assembly and the pedestal, thus reducing 45 conductive thermal transfer between the pedestal and the base assembly.

6. The apparatus of claim 1, wherein the axially-extending base assembly comprises a modular assembly comprising a plurality of axially-interconnected base modules disposed in 50 a cavity of the rotor core.

7. The apparatus of claim 6, wherein a base module is arranged to anchor the respective proximate ends of the elongated loops with respect to the rotor core by way of a tubular coupling.

8. The apparatus of claim 7, wherein the tubular coupling is 55 further arranged to provide an axial mechanical connection with respect to an axially-adjacent base module.

9. The apparatus of claim 7, wherein the tubular coupling comprises a segmented tubular coupling interconnectable by way of respective couplers. 60

10. The apparatus of claim 1, wherein the respective angles relative to the radial axis of said at least first loop and said at least second loop comprise congruent angles to provide symmetrical tangential support to the cradle.

11. The apparatus of claim 1, wherein said at least first 65 elongated loop and one or more further loops form a first group of elongated loops having proximate ends respectively

located on the first side of the radial axis, and said at least second elongated loop and one or more further loops form a second group of elongated loops having proximate ends respectively located on the second side of the radial axis.

12. The apparatus of claim 11, wherein the first and second groups of elongated loops comprise an equal number of loops.

13. The apparatus of claim 1, further comprising at least one spacer disposed about a portion of the cradle and interposed between the respective distal ends of the elongated loops to maintain axial separation between the elongated loops.

14. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromo- 15 tive machine, comprising:

a cradle configured to define a recess to receive the superconductor winding;

at least a first elongated loop and at least a second elongated loop each arranged at a respective angle relative to a radial axis to provide radial and tangential support to the cradle, wherein the elongated loops comprise a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least first loop and said at least second loop at respective distal ends of 20 the elongated loops; and

an axially-extending base assembly arranged to anchor said at least first loop and said at least second loop with respect to the rotor core at respective proximate ends of the elongated loops, which proximate ends are respectively located on first and second mutually opposite sides of the radial axis, wherein the axially-extending base assembly comprises a modular assembly comprising a plurality of axially-interconnected base modules disposed in a cavity of the rotor core, wherein a base module comprises an axially-forward face and an axially-rearward face, wherein the tubular coupling comprises at least a first tube located at the axially-forward face of said at least one base module and further located at the first of the mutually opposite sides to receive the proximate end of said at least first of the elongated loops, wherein the tubular coupling further comprises at least a second tube located at the axially-rearward face of said at least one base module and further located at the second of the mutually opposite sides to receive the proximate end of said at least second of the elongated loops. 30

15. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromo- 35 tive machine, comprising:

a cradle configured to define a recess to receive the superconductor winding;

at least a first elongated loop and at least a second elongated loop each arranged at a respective angle relative to a radial axis to provide radial and tangential support to the cradle, wherein the elongated loops comprise a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least first loop and said at least second loop at respective distal ends of the elongated loops; and 40

an axially-extending base assembly arranged to anchor said at least first loop and said at least second loop with respect to the rotor core at respective proximate ends of the elongated loops, which proximate ends are respectively located on first and second mutually opposite sides of the radial axis, wherein the respective angles relative to the radial axis of said at least first loop and said at least second loop comprise different angles to provide asymmetrical tangential support to the cradle. 45

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16. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromotive machine, comprising:

a cradle configured to define a recess to receive the superconductor winding;

at least a first elongated loop and at least a second elongated loop each arranged at a respective angle relative to a radial axis to provide radial and tangential support to the cradle, wherein the elongated loops comprise a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least first loop and said at least second loop at respective distal ends of the elongated loops; and

an axially-extending base assembly arranged to anchor said at least first loop and said at least second loop with respect to the rotor core at respective proximate ends of the elongated loops, which proximate ends are respectively located on first and second mutually opposite sides of the radial axis, wherein said at least first elongated loop and one or more further loops form a first group of elongated loops having proximate ends respectively located on the first side of the radial axis, and said at least second elongated loop and one or more further loops form a second group of elongated loops having proximate ends respectively located on the second side of the radial axis, wherein the first and second groups of elongated loops comprise a different number of loops.

17. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromotive machine, comprising:

a cradle configured to define a recess to receive the superconductor winding;

at least a first elongated loop arranged at a respective angle relative to a radial axis, wherein said at least first elongated loop comprises a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least first loop at a distal end of the elongated loop, wherein said at least first loop comprises an individual structure;

an axially-extending base assembly arranged to anchor said at least first loop with respect to the rotor core at a proximate end of the elongated loop, which proximate end is located on a first side of the radial axis; and

a support structure to provide jointly with said at least first loop radial and tangential support to the cradle.

18. The apparatus of claim 17, wherein the support structure comprises at least a second elongated loop comprising a respective material substantially resistant to heat flow, wherein the cradle is arranged to support said at least second loop at a respective distal end of said at least second elongated loop, wherein the base assembly is arranged to anchor said at

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least second loop with respect to the rotor core at a respective proximate end of said at least second loop, wherein the proximate end of said at least second loop is located on a second side of the radial axis, which is opposite to the first side.

19. The apparatus of claim 17, wherein the base assembly comprises a bumper support structure which constitutes the support structure.

20. The apparatus of claim 19, wherein the bumper support structure comprises at least one discrete bumper disposed on a periphery of the base assembly.

21. The apparatus of claim 17, further comprising a pedestal arranged to close a bottom side of the recess and support the superconducting winding in the cradle.

22. The apparatus of claim 21, wherein the base assembly comprises at least one seat arranged to support the pedestal during a static condition of the rotor or during a rotational condition comprising a relatively low revolution per minute (RPM) of the rotor.

23. The apparatus of claim 22, wherein the support structure comprises an extension of said at least one seat.

24. The apparatus of claim 23, wherein said at least one seat and the extension of said at least one seat form a continuous bumper support structure, which defines at least a portion of the periphery of the base assembly.

25. The apparatus of claim 21, wherein the bumper support structure comprises a first bumper portion which defines a seat arranged to support the cradle during a static condition of the rotor or during a rotational condition comprising a relatively low revolution per minute (RPM) of the rotor, and further comprising a second bumper portion which jointly with said at least first loop provide the radial and tangential support to the cradle.

26. An apparatus to support a superconductor winding in a spaced apart relationship from a rotor core of an electromotive machine, comprising:

at least a first elongated loop arranged at a respective angle relative to a radial axis, the elongated loop comprising a respective material substantially resistant to heat flow, wherein said at least first loop comprises an individual structure;

a support structure to provide jointly with said at least first loop radial and tangential support to the winding;

an axially-extending base assembly arranged to anchor said at least first loop with respect to the rotor core at a proximate end of the elongated loop, which proximate end is located on a first side of the radial axis; and

an assembly to receive the superconductor winding and to support said at least first loop at a respective distal end of the elongated loop.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 9,293,959 B2  
APPLICATION NO. : 13/748832  
DATED : March 22, 2016  
INVENTOR(S) : Rico et al.

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page and in the Specification, column 1, lines 1-3 please correct the title of the patent.

APPARATUS TO SUPPORT SUPERCONDUCTING WINDINGS IN A ROTOR OF AN  
ELECTROMOTIVE MACHINE

Signed and Sealed this  
Sixth Day of December, 2016

A handwritten signature in black ink, reading "Michelle K. Lee". The signature is fluid and cursive, with the first letters of each name being capitalized and prominent.

Michelle K. Lee  
*Director of the United States Patent and Trademark Office*